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Pneumatically Modulated Liquid Delivery System for Nebulizers

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14. ABSTRACT

A liquid delivery system for nebulizers typically used in inductively coupled plasma spectrometry is implemented with active, closed-loop feedback to generate a constant, stable flow rate over extended periods of time. An electronic pressure control unit is coupled with a pressure vessel and flow meter in three separate configurations. The first configuration uses a computer to monitor the flow rate and adjust the pressure based on a PID algorithm. The second configuration uses an embedded microcontroller in a separate control box, and the third configuration places all the components in a single box. Flow rates with less than 0.5% relative standard deviation are possible, and results are compared with a syringe pump and capillary-high pressure liquid chromatography pump.

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I. Introduction

Pneumatic nebulizers are widely used for sample introduction in inductively coupled plasma (ICP) mass spectrometry (MS) and optical emission spectrometry (OES). Nebulizers generate a fine aerosol, or mist, of liquid droplets that are subsequently vaporized. The aerosol is generated by passing a high-velocity sheath gas over the orifice of a liquid filled capillary. Due to the Venturi effect, liquid is pulled from the capillary orifice and the surface tension is disrupted to generate a fine liquid aerosol. Figure 1 shows an image of the aerosol generated from a PTFE nebulizer (Elemental Scientific, Omaha, NE USA) at 30 µL min^{-1} liquid flow and 1000 mL min^{-1} gas flow. The small droplets of the aerosol are clearly visible. Gas flow into the nebulizer is controlled with a rotameter or mass flow controller, while liquid flow is generated with either a syringe pump, peristaltic pump, or through self-aspiration. Each nebulizer is calibrated to a specific gas flow for self-aspiration, eliminating the need for an external pump. However, self-aspiration can be affected by tip fouling and a syringe pump or peristaltic pump maintain a constant liquid flow in the milliliters per minute range.

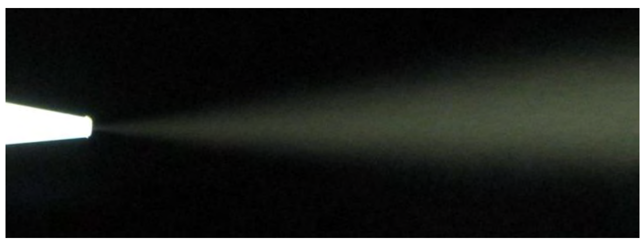

Figure 1: A PTFE nebulizer generating a fine aerosol, or mist, of water with 1000 mL min^{-1} air flow and 30 µL min^{-1} liquid flow. Nebulizers are typically used for inductive coupled plasma (ICP) spectrometry.

The Naval Research Laboratory (NRL) has been investigating the use of nebulizers for the generation of low-volatility analyte vapor streams (e.g. nitroaromatics). The goal is to generate a constant, stable vapor stream of analytes with extremely low vapor pressures. In order to achieve efficient conversion of liquid samples into vapors, nebulizers used in ICP-MS were investigated. Initially, a syringe pump was used to regulate liquid flow into the nebulizer. The concentration of analyte in the liquid phase was calibrated to generate trace concentrations of analyte vapor (parts-per-billion to parts-per-trillion levels). However, the syringe pump stepper motor introduced oscillations, as seen in Figure 2, and these oscillations were magnified by the relatively low flow rate (30 µL min^{-1}). At trace concentrations, the oscillations were detrimental and overshadowed any meaningful chemical information. Furthermore, the syringe pump with a 10 mL syringe needed constant refilling and would only run for approximately 5 hours. The 5 hour run time could be extended with a continuous flow setup using a pair of valves and two syringes. The continuous flow setup did not eliminate the oscillations, and an equilibration time of at least one hour was necessary every time the syringe pump switched directions, especially for trace analyte vapors.

Herein, a self-contained pneumatically modulated liquid delivery system (PMLDS) is described, which is capable of maintaining a constant flow rate over 24 hours with a closed-loop feedback system that is currently not commercially available. We present three iterations

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of the system: a computer-assisted configuration, an embedded microcontroller with functions spread over two independent boxes, and a third all-in-one configuration that is capable of standalone operation or interfacing with a computer. The PMLDS performance is compared with a syringe pump and a capillary high-pressure liquid chromatography (HPLC) pump.

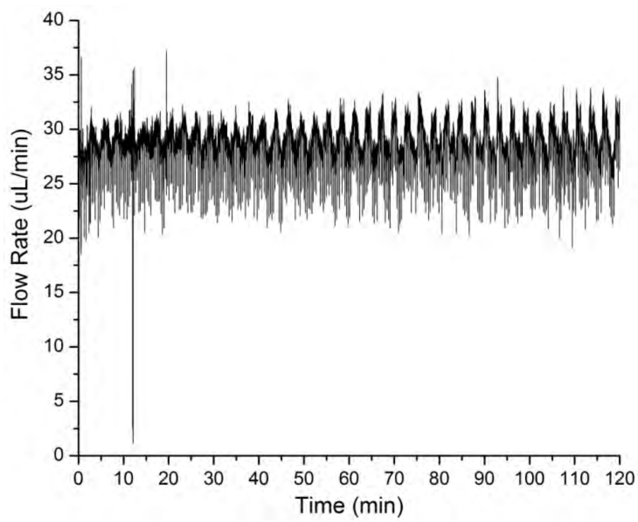

Figure 2: The flow rate for a syringe pump over 2 hours with a 10 mL syringe and a 30 µL min^{-1} flow rate. The oscillations in flow rate are attributed to the stepper motor used to move the piston within the pump and magnified by the relatively low flow rate.

II. Computer-Assisted Flow Control

Figure 3 shows a diagram representation of the pneumatic flow control with feedback. An electronic pressure control (EPC) unit is used to regulate the pressure inside a sealed vessel with a capillary. Liquid flow is generated by pressurizing the sealed vessel, forcing liquid up and out the capillary through the flow meter. The measured flow rate is recorded by the computer or microcontroller and a Proportional-Integral-Derivative (PID) controller algorithm calculates the necessary pressure to achieve the desired flow rate.

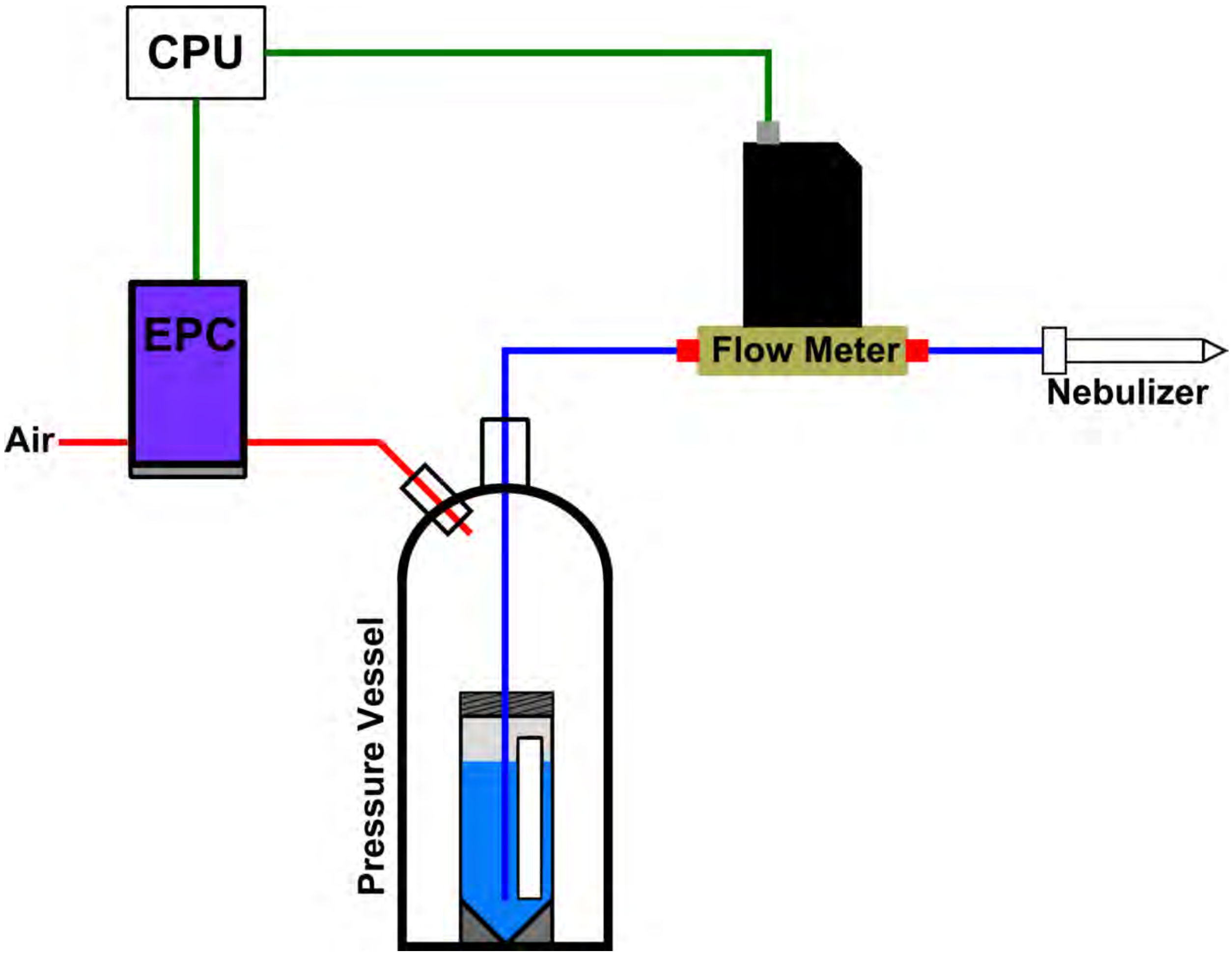

Figure 3: A diagram outlining the general components of a pneumatically modulated liquid delivery system for a nebulizer. The basic components include an electronic pressure control (EPC) unit, a flow meter, pressure vessel, and a PID controller, either a computer or microcontroller. A mass flow controller is also used to supply 1000 mL min^{-1} of nitrogen flow through the nebulizer, but has been omitted. The red line indicates the gas line, or pressure, the green line indicates electrical connections, and the blue line is the liquid flow.

The EPC (Parker Hannifin Corp., Cleveland, OH USA, 0-15 PSIG) unit modulates the pressure based on a 0-5 V analog input voltage and requires <400 mA at 24 V to operate. The EPC unit is only capable of controlling the pressure to 10% of its full scale value. Any control voltage less than or equal to 0.5 V is consider 0.0 V by the EPC unit. Thus, with a 15 PSIG EPC unit, the full controllable pressure range is 1.6 to 15 PSIG with a resolution of approximately 0.23 PSIG. A control voltage resolution of 0.075 V (75 mV) is needed for 0.23 PSIG pressure resolution. A 6-bit digital-to-analog converter (DAC) could be used, but relatively inexpensive, higher resolution DACs are more common and readily available. For example, an 8-bit DAC in an 8-pin dual-inline package (DIP), such as the MAX517 integrated circuit, costs less than one US dollar and provides approximately 0.020V (20 mV) resolution, which is more than adequate for the 15 PSIG EPC unit. The Measurement Computing DAC (USB-3110) has 16-bit resolution and cost significantly more, but is easy to install and operate without a custom circuit and is capable of multiplexing multiple EPC units.

The initial configuration placed the EPC unit and gas connections in one 3x4x5 inch aluminum box with the flow meter mounted on top. Figure 4 shows a diagram of the components placed inside the box along with electrical connections, but the gas connections have been omitted for clarity. The breakout board was used to convert the RJ11 4P4C connector from the EPC unit to a screw terminal connection so that stripping, cutting, and soldering were minimized. A panel mount, isolated BNC connector was used to connect the control voltage input of the EPC unit to a computer or embedded microcontroller. Figure 5 shows an image of the assembled EPC box with gas connections.

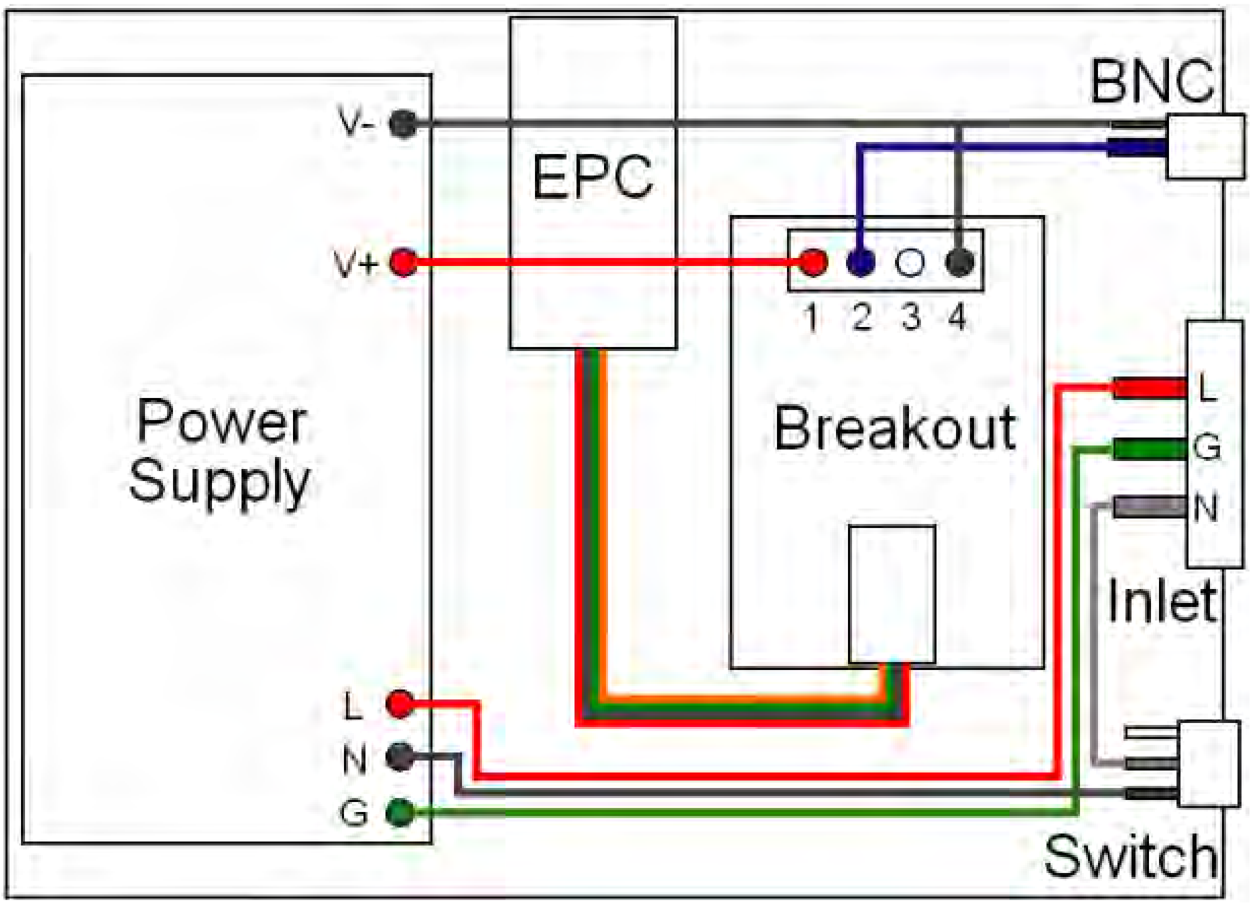

Figure 4: A diagram of the components and electrical connections for the electronic pressure control (EPC) box. All the components were mounted and placed in a 3x4x5 in. aluminum box.

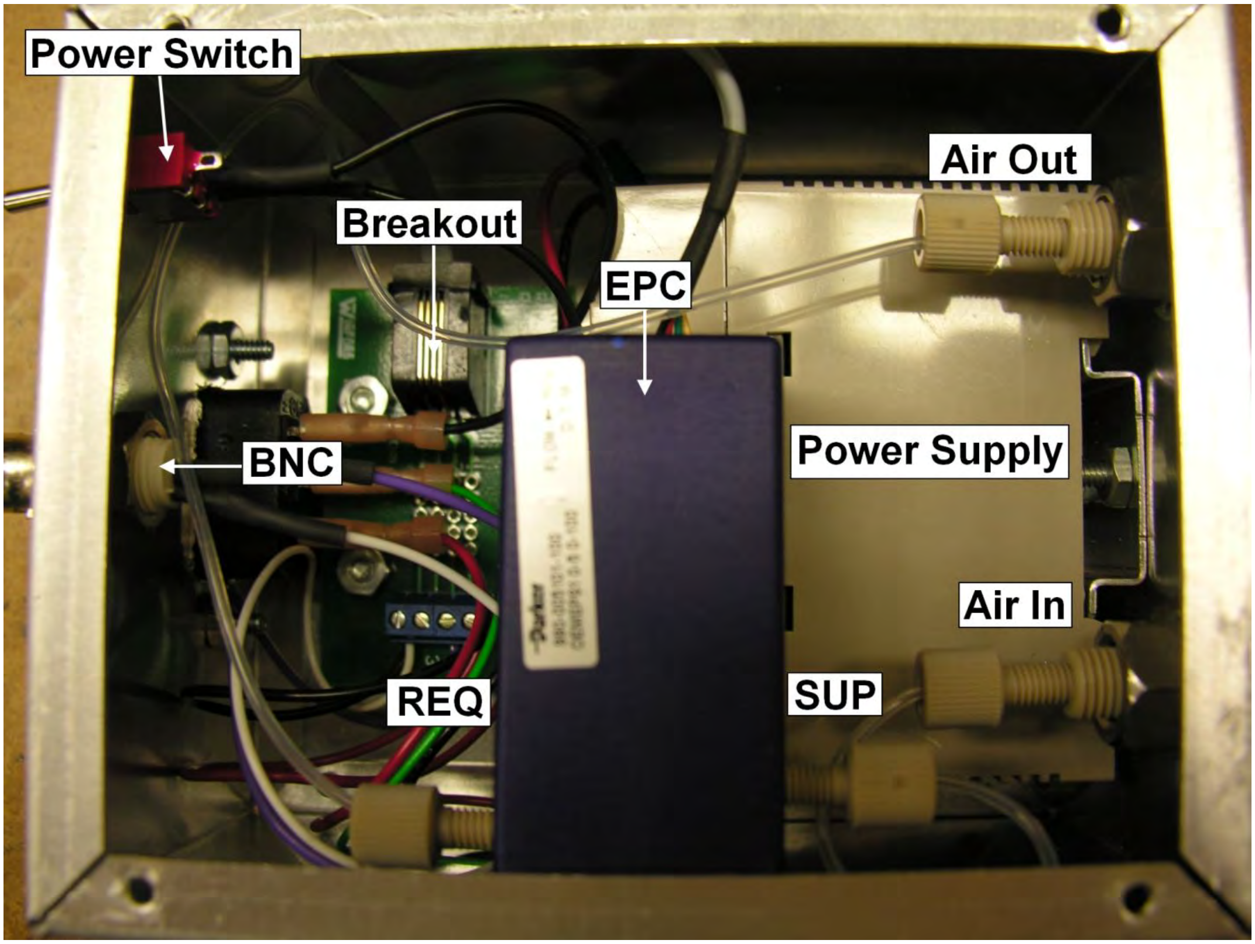

Figure 5: The electronic pressure control (EPC) box with electrical and gas connections. The required (REQ) and supplied (SUP) connections of the EPC unit have been labeled. The gas inlet is connected to the supplied side of the EPC unit while the gas outlet is connected to the required side. The breakout board is used to have screw terminals for the EPC unit channels. The BNC connector passes the 0-5 V control voltage to the breakout board and ultimately the EPC unit.

A four channel, analog output USB DAC (Measurement Computing, USB-3110) was used to supply a 0-5 V control voltage to the EPC unit based on the PID controller. A BNC cable with stripped wire leads connected the USB DAC to the BNC port of the EPC box. This configuration requires the use of a computer, which introduces significant overhead and cost to the system, but enables data logging of the flow rate and pressure. A custom LabVIEW program was created with PID control to monitor the flow rate and automatically adjust pressure. The program was designed to log data over time and compensate for bubbles that may have been introduced during loading of liquid samples. Additionally, three separate power outlets were required to run the system (five if the computer and monitor were included). The computer-assisted configuration was used to establish the feasibility of the design, but the number of required power outlets and relatively large space and overhead introduced by the computer made this configuration undesirable for routine use.

III. Embedded Microcontroller Flow Control

Due to space restrictions and availability of power outlets to run the system, an embedded solution with an all-in-one power supply was designed and implemented. The Arduino Uno is a well-established hobbyist microcontroller, focused on ease-of-use and teaching non-computer programmers about embedded applications. Consequently, there is a vast online community and documentation for the Uno with readily available components for assembling embedded circuits. The Arduino Uno uses an Atmega328 microcontroller with thirteen digital TTL control lines, six 10-bit resolution 0-5 V analog inputs, TTL serial communication, I^2C serial communication, and an open source integrated development environment (IDE). The microcontroller has additional features and components that are not listed due to relevance. The Arduino Uno is feature-rich and more than capable of monitoring flow rates and adjusting control voltages.

The Arduino Uno is capable of serial communication with other devices up to 19200 bits per second on its Digital 0 (RX) and 1 (TX) channels. However, the Digital 0 and Digital 1 channels are also used for uploading code to the microcontroller. The microcontroller cannot be connected to the computer via its USB connector and a serial device on Digital 0 and Digital 1 at the same time. Other digital channels can be used, but are limited to 9600 bits per second. The Sensirion ASL1600 flow meter (Zurich, Switzerland) uses 19200 bits per second. In order to communicate with the flow meter, the serial communication on Digital 0 and Digital 1 channels must be used, but the flow meter cannot be connected to the microcontroller at the same time the microcontroller is connected to the computer. A series of two jumpers and two sets of header pins were placed in-line from the Digital 0 and Digital 1 channels of the microcontroller and the serial communication circuit with the flow meter. Uploading new code to the microcontroller involves removing the jumpers from the header pins, while communication with the flow meter requires connecting the header pins with jumpers. Future configurations could replace the header pins and jumpers with a single board mounted switch.

The Arduino Uno uses TTL (0 or 5 V) voltage levels to communicate with serial devices on Digital 0 (RX) and 1 (TX) channels. The flow meter uses the RS-232 protocol, which is a bi-directional, inverted signal up to 15 V. A MAX232 integrated circuit (IC) was used to convert the TTL signals from the Arduino Uno to RS-232 signals for the flow meter. The MAX232 is a dual channel chip, providing an additional channel to be used for RS-232 communication with another device, such as a computer or second flow meter.

An 8-bit, white-on-black, 16x2 (columns, rows) LCD was used to display target flow (TF), actual flow (AF), control voltage (V), and pressure (P). The pressure was not actively monitored by the microcontroller, but instead calculated from the control voltage based on the full range of the EPC unit. Only four bits from the LCD screen were needed to display all the required values. Thus, only twelve of the sixteen pins were used for the LCD screen, which was nicely divided into two pairs of six continuous pins. Figure 6 shows the LCD screen display with the backlight enabled.

The Arduino Uno has pulsed width-modulated (PWM) outputs on six of the digital channels. PWM in combination with an appropriate capacitor and resistor (RC circuit) can be used to generate an analog voltage between 0-5 V. However, all of the PWM channels were used for the two flow rate selection switches and the LCD screen as normal digital input/output channels. Instead, a DAC IC with 2-wire I^2C serial communication was used to output a control voltage between 0-5 V to the EPC unit. Analog inputs 4 (SDA) and 5 (SCL) can be used for I^2C communication with the Arduino Uno using the Wire Library provided with the IDE. A MAX517 single channel DAC with a reference voltage of 5 V from the microcontroller was used. The I^2C communication protocol is generally an 8-bit standard, but the Arduino Wire Library uses only seven bits. So, the eight bit address for the MAX517 chip had to be right shifted one bit because the Wire library automatically appends the eighth bit, shifting the address to the left. The source code for the microcontroller has been commented with this discrepancy. The 8-bit resolution, as mentioned earlier, is more than adequate for controlling the EPC unit.

Two momentary-off-momentary (Mom-Off-Mom) switches allow the user to select the target flow rate, as seen in Figure 6. One switch adjusts the ten's position, while the second switch adjusts the one's position of the target flow rate. Incrementing and decrementing the target flow rate happens once per click of the switches, either up or down, respectively. The microcontroller looks for a change from 5 V (TTL High, or true) to 0 V (TTL Low, or false) to update the target flow value in microliter per minute and four 10 KΩ pull-up resistors set the input to 5 V when in the middle, off position.

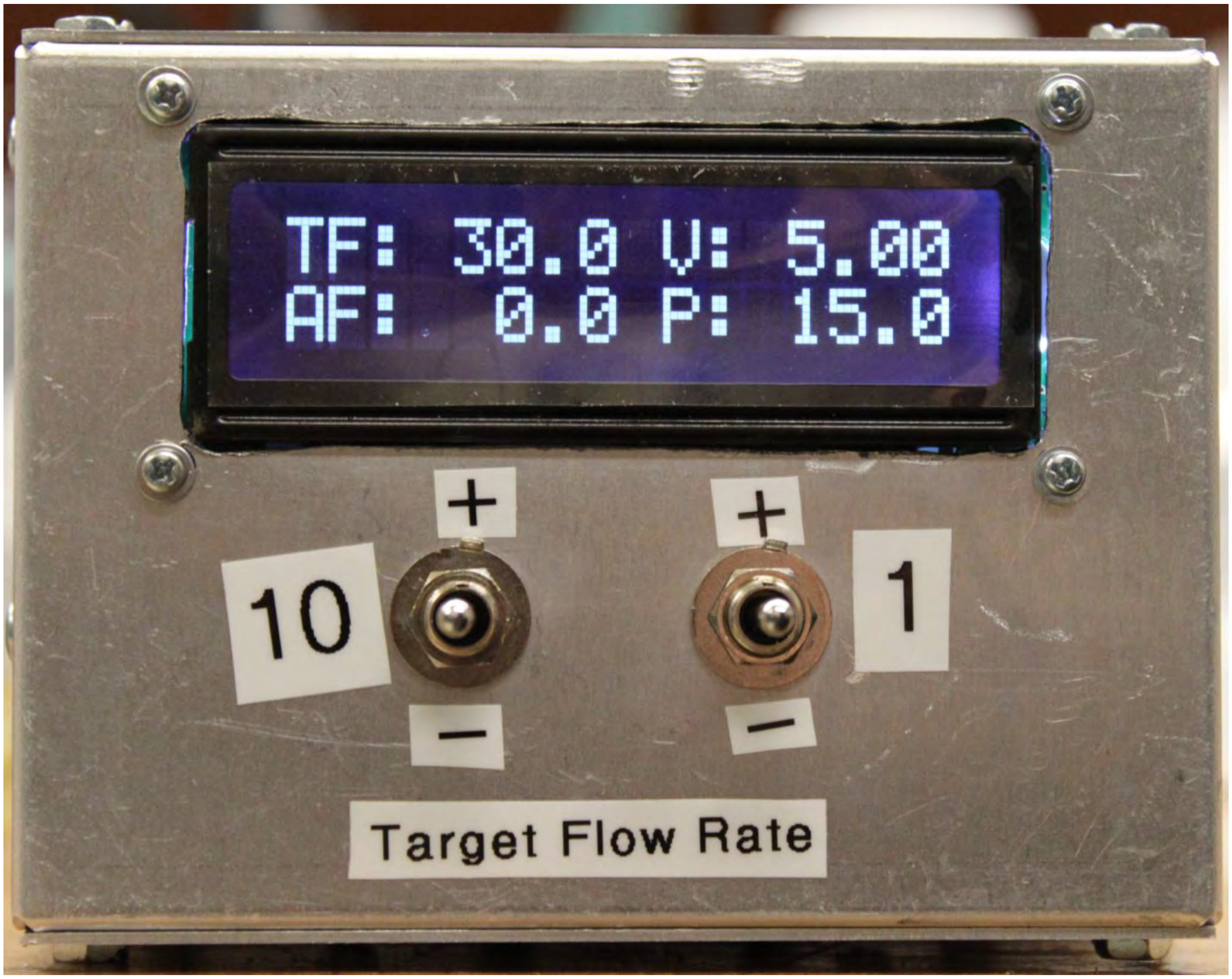

Figure 6: An image of the white-on-black 16x2 LCD during operation of the embedded controller configuration. The target flow (TF) is displayed in microliter per minute and set by the user with the two momentary-off-momentary input switches, one's place and ten'

The relatively simple circuit with the two ICs and required headers, connectors, resistors, and capacitors was assembled on a commercially available breadboard designed specifically for the Arduino Uno (ProtoShield v2, Sparkfun.com). Figure 7A shows the layout of electrical components on the breadboard used in the configuration with the microcontroller in a separate box from the EPC unit. The various electrical components were connected following the electrical diagram in Figure 8 with wire-wrap wire and soldering. The Arduino Uno, breadboard, LCD, power supply, and switches were placed in a single 3x4x5 inch aluminum box. A male DB9 connector was mounted on the back panel along with an isolated BNC connector for connection to the flow meter and EPC box, respectively. A DB9-to-M8 connector was made with a 9 V power channel on Pin 1 to power the flow meter though the embedded controller box instead of an external power supply; thus, the number of required power outlets was reduced to two (one for the embedded microcontroller box and one for the EPC box).

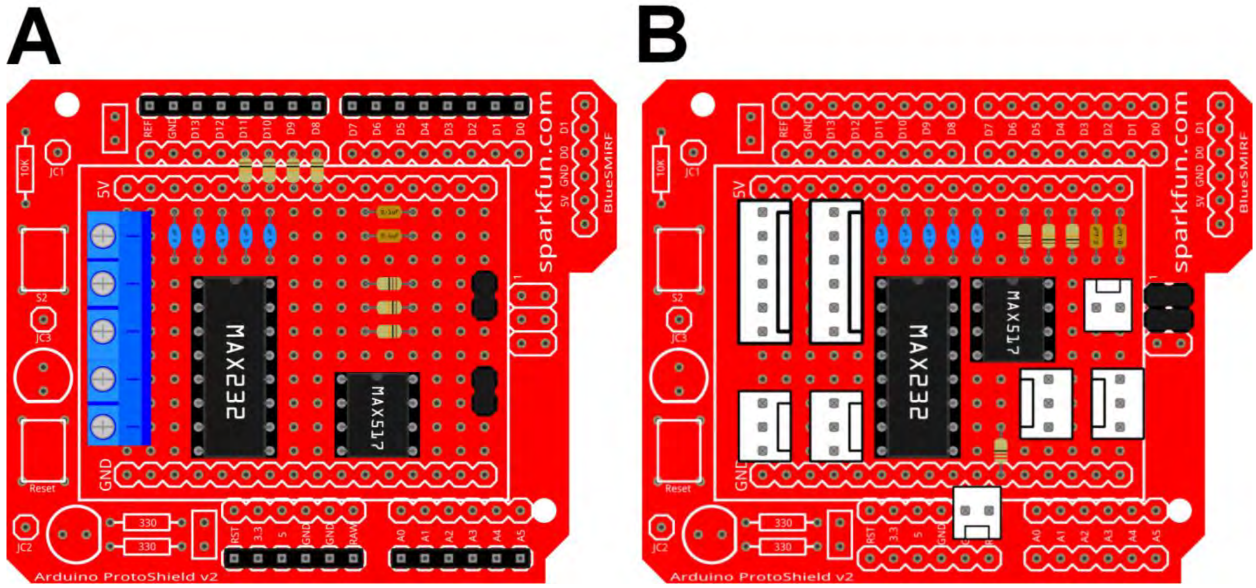

Figure 7: A diagram of the electrical components mounted and connected on a breadboard designed specifically for the Arduino Uno microcontroller. (A) The layout used for the microcontroller housed in a separate box from the EPC unit. (B) The layout used for the all-in-one configuration with the microcontroller and EPC unit mounted in a single box. The screw terminals have been replaced with polarized header pins.

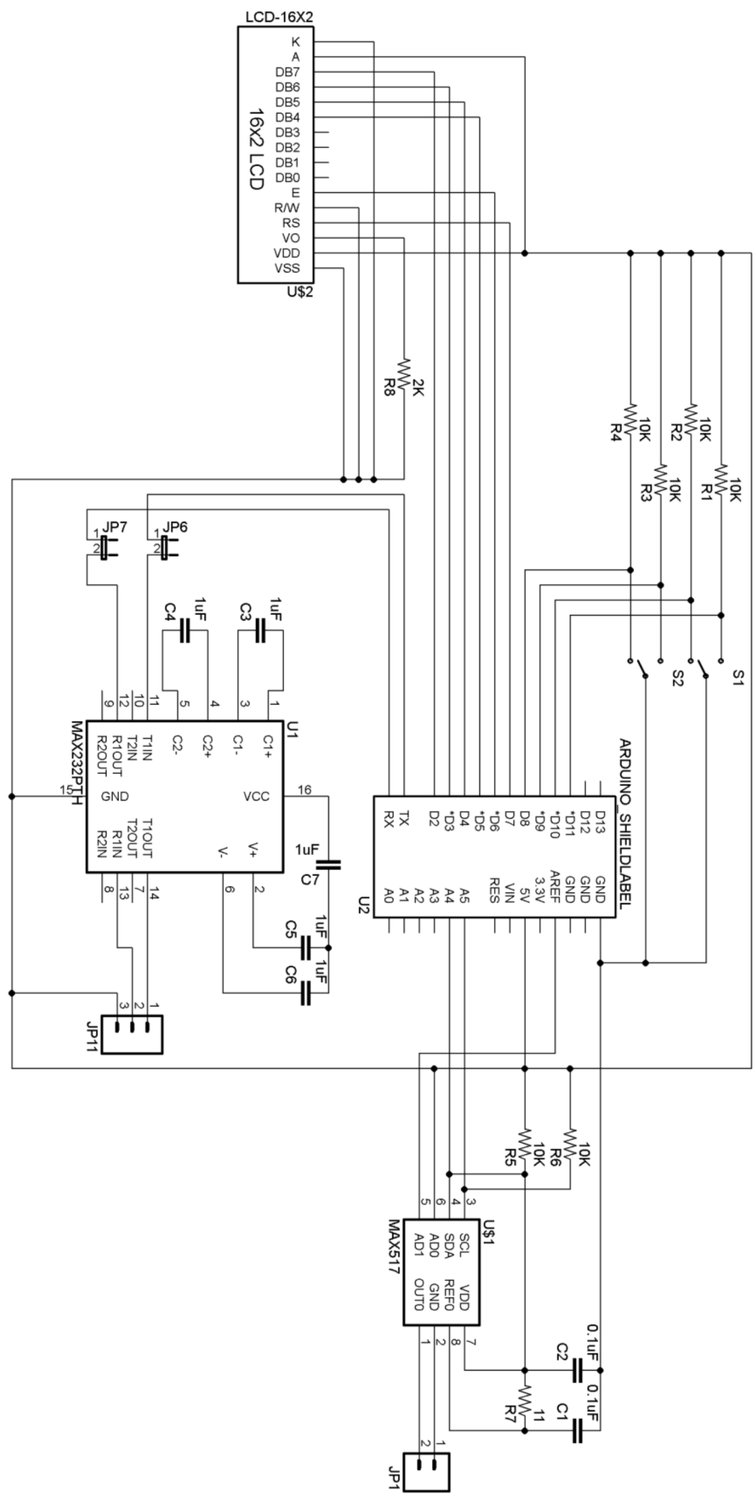

Figure 8: The electrical diagram for the embedded controller mounted in a separate box from the EPC unit using a 9 V, 1.2 A power supply. The different components are shown hard wired to the Arduino Uno, but components are mounted on a breadboard with header pins that align with the Arduino Uno board following Figure 7A. Actual connections to panel mounted components are made via screw terminals and header pins.

The final configuration placed the EPC unit inside the microcontroller box to have one box and one power outlet to run the nebulizer. Figure 9 shows images of the final configuration. A second DB9 connector was mounted on the back panel and used for communication with a computer via the RS-232 protocol and the extra RS-232-to-TTL converter channel on the MAX232 IC, as seen in Figure 9B. The isolated BNC connector was eliminated since the EPC unit is connected directly to the breadboard in Figure 7B. The EPC unit requires 24 V and <400 mA, while the microcontroller and flow meter are capable of operating with a voltage between 6-20 V, typically 9 V. Originally, a 9 V, 1.5 A power supply (TDK-Lambda, ZPSA20-9) was used to power the microcontroller, LCD, and flow meter. The 9 V supply was replaced with a 24 V, 0.9 A power supply (TDK-Lambda, ZPSA20-24) to reduce the number of power outlets. A voltage regulator (Fairchild Semiconductor, LM7809CT) was added to the circuit to drop the voltage from 24 V to 9 V for the microcontroller and flow meter. The voltage regulator was mounted directly underneath the Arduino Uno board and to the bottom plate of the aluminum box to properly heat sink the IC. The relatively large drop in voltage from 24 V to 9 V requires adequate cooling of the voltage regulator. The LCD screen was powered from the 5 V regulated output of the microcontroller, along with the backlight. Figure 10 shows the electrical schematic of the all-in-one configuration of the microcontroller and EPC unit, and Table 1 summarizes the Arduino Uno pin connections. All three configurations, computer-assisted, embedded, and all-in-one, were used depending on the application. A complete parts list for all three configurations can be found in Appendix A.

A C++ library was written for communicating with the Sensirion ASL1600 flow meter. Another library was created to implement a simple PID controller algorithm suitable for use with the Arduino Uno. Since the EPC unit and the flow meter only had one decimal of precision, the pressure and flow rate were stored as integers with values ten times their actual values, respectively. The values were divided by ten when needed for display purposes or calculations related to the PID control. The control voltage was similarly stored as an integer, but with a value 100 times the actual value. The integer storage of the three variables was done to minimize memory and space usage and speed up calculations since floating-point calculations are relatively slow with microcontrollers. The total compiled program is approximately 10 Kb, leaving 20 Kb for future upgrades and additional features. The source code is available in Appendix B or in electronic format from the authors.

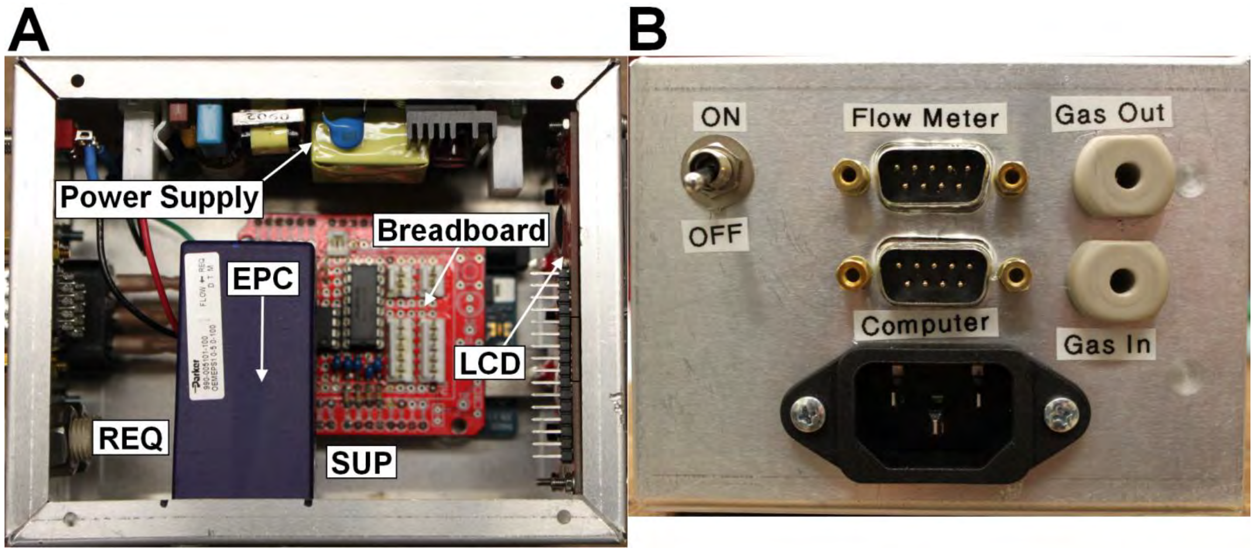

Figure 9: (A) Photograph of the all-in-one configuration with the electronic pressure control (EPC) unit, Arduino Uno, voltage regulator, breadboard, and 24 V, 0.9 A power supply mounted in one 3x4x5 inch aluminum box. The complete electrical and pneumatic connections have been omitted for clarity. (B) The back panel of the all-in-one configuration with gas connections, power switch, power connection, and two DB9 connectors for communication with the flow meter and computer via the RS-232 protocol.

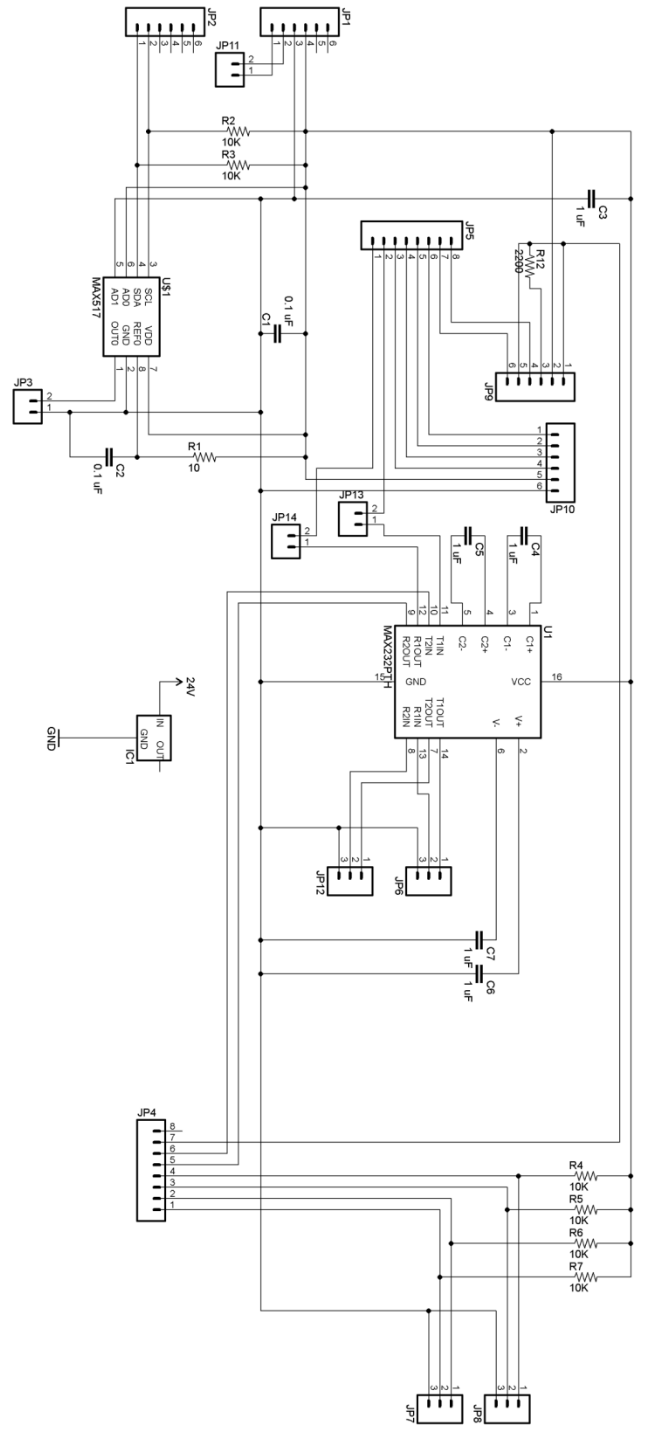

Figure 10: The electrical diagram of the all-in-one configuration with the microcontroller and EPC housed in a single 3x4x5 inch aluminum box with a 24 V, 0.9 A power supply. The Arduino Uno, LCD, and switches have been omitted for clarity and to reflect the use of KK connectors™ instead of hard wiring directly to a breadboard. The OUT pin of the voltage regulator is connected to JP01 via a KK connector™ and cable.

Table 1: A summary of the Arduino Uno microcontroller pin connections to each component in the all-in-one configuration.

Arduino Uno Pin	Function	Component Pin
Reset	Not connected	
3.3V	Not connected	
5V	Power supply	LCD Pin 2, LCD Pin 15, 1's increment, 1's decrement, 10's increment, 10's decrement, MAX517 Pin 6, MAX517 Pin 7, MAX517 Pin 8, MAX232 Pin 16
GND	Ground	LCD Pin 1, LCD Pin 3, LCD Pin 5, LCD Pin 16, MAX517 Pin 2, MAX517 Pin 5, MAX232 PIN 15
GND	Ground	Voltage regulator
Vin	9V input	Voltage regulator
A0	Not connected	
A1	Not connected	
A2	Not connected	
A3	Not connected	
A4	SDA	MAX517 Pin 4
A5	SCL	MAX517 Pin 3
D0	TTL RX	MAX232 Pin 12
D1	TTL TX	MAX232 Pin 11
D2	LCD	LCD Pin 14
D3	LCD	LCD Pin 13
D4	LCD	LCD Pin 12
D5	LCD	LCD Pin 11
D6	LCD	LCD Pin 6
D7	LCD	LCD Pin 4
D8	10's switch	10's increment
D9	10's switch	10's decrement
D10	1's switch	1's increment
D11	1's switch	1's decrement
D12	Not connected	
D13	Not connected	
GND	Not connected	
AREF	Not connected	

IV. Pressure Vessels

Four pressure vessels were considered for use with the PMDLS. A 50 mL Nalgene centrifuge tube was tested, but based on documentation it could not hold 50 PSIG of pressure. Theoretically, the EPC unit is supplied with house air, which is down regulated to 50 PSIG. If the EPC unit were to fail, 50 PSIG could be supplied to the pressure vessel, while only a maximum of 15 PSIG is supplied when the EPC unit is in use. A pressure vessel capable of at least 50 PSIG was desirable for safety considerations, and necessary if higher flows and pressures were needed in future applications. A 500 mL Nalgene bottle was also considered, but a noticeable deformation was observed under 15 PSIG of pressure.

A glass, 350 mL round bottom flask was found capable of holding 150 PSIG (Chemglass Scientific Equipment, Inc.). The glass round bottom flask had adequate volume to run continuously for several days at 30 µL min^{-1} and a visible indication of liquid level in the vessel. An inert plastic "T" connector (P-714, IDEX Health & Science) was used to connect the liquid flow and pressure line to the cap provided with the round bottom flask. The plastic cap was drilled and tapped for an adaptor (U-511, IDEX Health & Science) to connect to the "T." Plastic capillary tubing (360 µm OD, 150 µm ID) was inserted through the "T" and into the round bottom flask for the liquid connection, while 1/16 inch OD thick-walled PTFE tubing was used for the gas connection. The completely assembled round bottom flask can be seen in Figure 11A. A complete parts list for the round bottom flask can be found in Appendix A. The glass round bottom flask must be flushed and rinsed after each use to reduce cross-contamination at trace concentrations, which is cumbersome and time consuming. A disposable option would provide greater utility and flexibility.

Finally, a metal, refillable spray paint canister rated for 100 PSIG was evaluated. The canister was modified slightly to hold 50 mL plastic centrifuge tubes and 1/16 inch OD PTFE tubing for liquid flow. The 50 mL centrifuge tube offers improved reusability of the pressure vessel without flushing or rinsing, minimizes cross contamination, and the same containers can be used for solution preparation. Figure 11B shows the modified refillable spray paint canister with liquid and gas connections. Again, a complete parts list can be found in Appendix A. The metal canister is not transparent and the liquid level inside the 50 mL plastic centrifuge tubes cannot be monitored visually. With the exception of the 500 mL Nalgene bottle, the three other pressure vessels could be used depending on the application and experiment, but the glass round bottom flask and metal canister are better suited if a failure occurs and easily adapted for applications requiring higher pressures and flow rates.

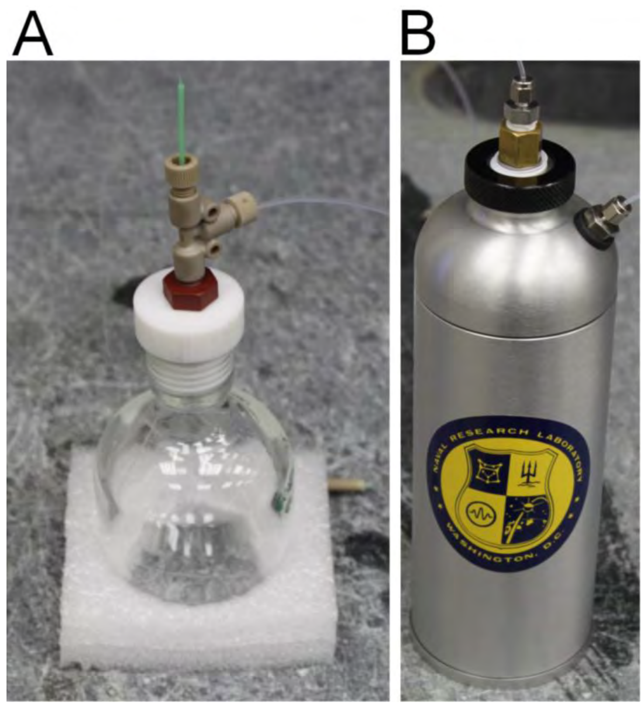

Figure 11: Pressure vessels for the PMLDS: (A) a 350 mL glass round bottom glass rated to 150 PSIG and (B) a refillable spray paint canister rated for 100 PSIG. An inert plastic “T” connection is used with the round bottom flask for fluidic and gas connections. PTFE capillary tubing (360 µm OD, 150 µm ID) was used as the liquid connection for the round bottom flask and thick-walled PTFE 1/16 inch OD tubing for the gas connections. The refillable spray paint canister used only thick-walled PTFE 1/16 inch OD tubing for both the liquid and gas connections.

V. Results

Figure 12 shows the flow rate over approximately a 20 hour period for a syringe pump, capillary-HPLC pump, and the PMLDS. All three systems were connected to the PTFE nebulizer to generate a water aerosol with representative flow restrictions. The relative standard deviations of the flow rates for the three systems are 6.6%, 5.0%, and 0.5% for the syringe pump, HPLC pump, and PMLDS, respectively. Clearly, the PMLDS provides a more stable, constant flow over an extended period of time. Oscillations with a relatively large period for the syringe pump can be seen in Figure 12A. These oscillations are a consequence of the syringe pump changing directions while operated in a continuous flow mode. The continuous flow mode is necessary to run longer than 5 hours with a 10 mL syringe, and could not reliably be operated at flow rates <60 μL min^{-1}. Due to the dead volume in the continuous flow system, at least 1 hour is needed after each change in direction to reestablish a constant flow and ultimately a stable vapor stream. During the most stable period of operation, between switching events, flow oscillations resulted in 6.6% RSD.

Random spikes in flow rate are observed with the capillary-HPLC pump (Figure 12B). The HPLC pump is designed to work at relatively high pressures (1000 PSIG) and higher flow rates (1 mL min^{-1}), not the atmospheric pressure and microliters per minute flow rate required for the nebulizer. These conditions associated with the nebulizer contribute to the inconsistent flow rate of the HPLC pump. Furthermore, the cost of the PMLDS (~$700 US) is significantly less than the syringe pump (~$5K US) and HPLC pump (~$10K US), if the flow meter is not included. OEM flow meters are available at reduced, bulk pricing and printed circuit boards (PCBs) could be used instead of breadboards, which are time intensive to assemble. Overall, the observed stability and relatively low cost of the PMLDS makes it an attractive option for generating aerosols of analytes with a nebulizer.

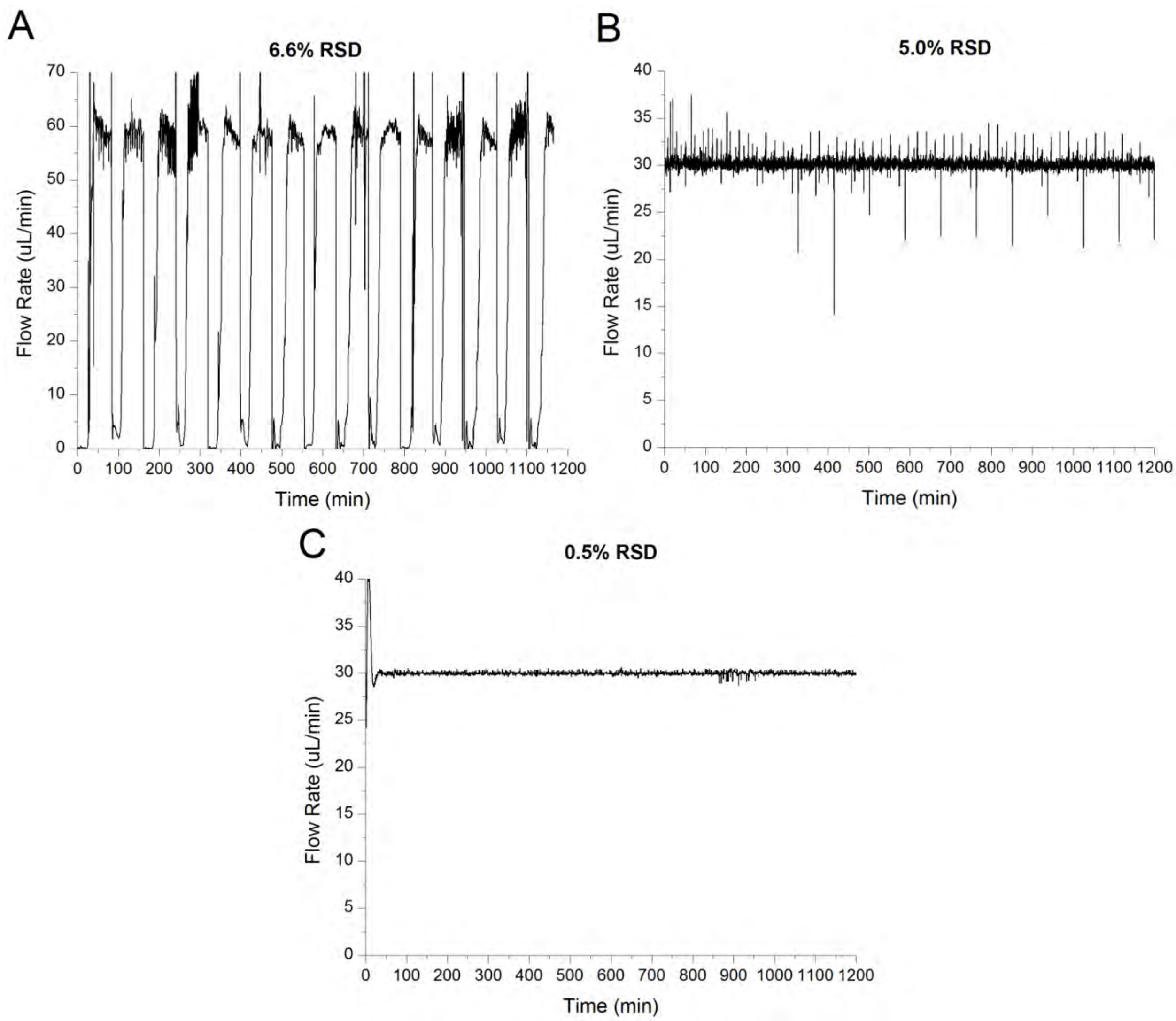

Figure 12: Flow rate versus time for a nebulizer driven with (A) a syringe pump, (B) a capillary HPLC pump, and (C) a pneumatically modulated liquid delivery system (PMLDS) with the relative standard deviation for the flow rate over approximately 20 hours. The oscillations of the syringe pump are clearly visible as the pump changes directions in continuous flow mode, while the spikes in flow rate for the HPLC pump are most likely due to a lack of pressure since the pump is designed to work at ultra high pressures (>100 PSIG). The initial pulse in flow rate for the PMLDS is the activation of the PID controller, where a short stabilization period is needed. The relative standard deviation for the syringe pump is calculated during the periods of flow established after equilibration and does not include the switching time.

VI. Conclusions

A pneumatically modulated liquid delivery system (PMLDS) was designed and implemented to generate a constant, stable flow for a pneumatic nebulizer. Three iterations of the PMLDS were built: a computer-assisted configuration capable of data logging, an embedded microcontroller configuration eliminating the needed for an expensive computer, and an all-in-one configuration with the electronics and pneumatics in a single box. The all-in-one configuration required only a single power outlet to run the electronics, pneumatics, and flow meter. A simple PID algorithm was implemented to calculate the pressure necessary to achieve a target flow rate. Several pressure vessels were investigated. A modified refillable spray paint canister provided the greatest balance between safety and usability. The stability of the liquid flow of the PMLDS connected to a nebulizer was compared to a syringe pump and capillary-HPLC pump. An order of magnitude improvement of the relative standard deviation for the average flow rate was observed for the PMLDS over an equilibrated syringe pump and HPLC-pump. The PMLDS can easily be extended to microfluidic applications and nanoliter per minute to milliliter per minute flow rate ranges. The PMLDS is a flexible and reliable system for delivering a constant, stable liquid flow over hours of operation and is ideally suited for nebulizers.

VII. Acknowledgements

The authors would like to acknowledge Dr. Braden C. Giordano for supplying the HPLC pump and procuring the flow meter.

APPENDIX A: Complete Parts List

Table A-1: Parts list for the Electronic Pressure Control (EPC) unit box and pressure vessels.

Part Description	Quantity	Part Number	Manufacturer
Electronic Pressure Control (EPC) Unit (0-15 PSIG)	1	990-005101-015	Parker Hannifin Corp.
Breakout Board	1	BRK4P4C-R-DIN	Winford Engineering
Power Connector Port	1	JR-101	Multicomp
Toggle switch On-On SPDT	2	A101SYZQ04	TE Connectivity
3 x 4 x 5 inch Aluminum Box	1	AU-1028	Bud Industries
Female spade crimp connector	3	19003-0107	Molex
Fork crimp connectors	5	31N2554	SPC Technology
10-32 coned Bulkhead Union, PEEK	2	P-440	IDEX Health & Science
10-32 PEEK Nut and Ferrule	1	F-331x	IDEX Health & Science
PTFE tubing 1/16 inch OD	5 ft	1503	IDEX Health & Science
BNC Connector, isolated, panel mount	1	713-9080	Amphenol
24 V, 0.9 A power supply, DIN rail	1	S82K-00324	Omron
6-32 screw, ½ inch	6	91770A148	McMaster-Carr
6-32 screw, ¼ inch	2	91770A144	McMaster-Carr
4-40 socket cap screw, ¼ inch	2	92949A106	McMaster-Carr
M3x4 socket cap button screw, 16 mm	2	92095A184	McMaster-Carr
½ inch spacer 0.14 inch ID, 0.25 inch OD	2	92510A445	McMaster-Carr
Nylon spacer, 1/8 inch	4	94639A299	McMaster-Carr
Serial-to-USB adaptor	1	USA-19HS	Keyspan
Flow meter	1	SLG1430-150	Sensirion
USB DAQ Board	1	USB-3112	Measurement Computing Corp.

Table A-2: Parts list for the embedded controller box, including the all-in-one configuration.

Part Description	Quantity	Part Number	Manufacturer
9V, 1.5A Power Supply	1	ZPSA20-9	TDK-Lambda
24V, 0.9A Power Supply	1	ZPSA20-24	TDK-Lambda
Toggle switch Mom-Off-Mom	4	A105SYZQ04	TE Connectivity
Toggle switch On-On SPDT	2	A101SYZQ04	TE Connectivity
Header pins, 36 pos	10	68001-436HLF	FCI
4 Pin Molex KK Connector	2	09-50-3041	Molex
3 Pin Molex KK Connector	2	09-50-7031	Molex
Terminal crimp connector	14	08-50-0107	Molex
Female spade crimp connectors	6	19003-0107	Molex
10K Ω Resistor	12	CFR-25JB-10K	Yageo
2K Ω Resistor	2	MFR-25FBF-2K10	Yageo
11 Ω Resistor	2	PCB15KB10R0	Stackpole Electronics
0.1 µF capacitor	4	SR215E104MAR	AVX Corporation
RS232-to-TTL chip	2	MAX232CPE+	Maxim
1-CH 8-Bit I2C DAC Chip	2	MAX517BCPA+	Maxim
1 µF capacitor	10	FK24Y5V1H105Z	TDK Corporation
IC Socket 16 Pos 0.300’’	2	110-93-316-41-00100	Mill-Max
IC Socket 8 Pin 0.300’’	2	110-44-308-41-00100	Mill-Max
Power Connector Port	2	JR-101	Multicomp
4 x 5 x 3 inch Aluminum utility box	2	AU-1028	Bud Industries
DB9 Male connector	3	G17S0910110EU	Amphenol
Fork Tongue crimp connector	2	31N2550	Newark Electronics
Microcontroller	2	Uno	Arduino
White on Black LCD Display	2	LCD-00709	Sparkfun
Arduino Stackable Headers, 8 pos	2	PRT-09279	Sparkfun
Arduino Stackable Headers, 6 pos	2	PRT-09280	Sparkfun
Screw terminal 0.300’’ pitch 2 pos	1	PRT-08432	Sparkfun
Screw terminal 0.300’’ pitch 3 pos	1	PRT-08433	Sparkfun
BNC connector, isolated	1	713-9080	Amphenol
Nylon 1/8 inch spacers	16	94639A299	McMaster-Carr
M2x4 screw	4	92005A033	McMaster-Carr
M2x16 screw	4	92005A037	McMaster-Carr
M2 nut	8	90591A111	McMaster-Carr
M2 washer	16	91166A180	McMaster-Carr
M3x10 screw	16	92005A120	McMaster-Carr
M3 nut	16	90591A121	McMaster-Carr
M3 washer, zinc	14	91166A210	McMaster-Carr
M3 nylon washer	2	95610A130	McMaster-Carr
4-40 socket cap screw ¼ inch	4	92949A106	McMaster-Carr

4-40 metal washer	4	94744A155	McMaster-Carr
10-32 coned Bulkhead Union	2	P-440	IDEX Health & Science
1/16 inch OD PTFE tubing	5 ft	1503	IDEX Health & Science
10-32 PEEK Nut and Ferrules	1	F-331x	IDEX Health & Science
Connector Receptacle Housing 6 pos	2	1375820-6	TE Connectivity
Connector Receptacle Housing 3 pos	4	1375820-3	TE Connectivity
Connector Receptacle Housing 2 pos	2	1375820-2	TE Connectivity
Connector Header Vertical 6 pos	2	640454-6	TE Connectivity
Connecter Header Vertical 3 pos	4	640454-3	TE Connectivity
Connecter Header Vertical 2 pos	2	640454-2	TE Connectivity

Table A-3: Parts list for the pressure vessels.

Part Description	Quantity	Part Number	Manufacturer
1/8 inch NPT male to 1/16 inch Swagelok Male stainless steel	1	SS-400-1-2	Swagelok
1/8 inch Swagelok male to 1/8 inch NPT female bulkhead stainless steel	1	SS-100-1-2BT	Swagelok
1/8 inch Swagelok male to 1/16 inch Swagelok male bulkhead stainless steel	1	SS-200-61-1	Swagelok
5/16 inch ID PTFE washer	2	96371A203	McMaster-Carr
5/16 inch ID, 5/8 inch OD stainless steel washer	1	92141A029	McMaster-Carr
Large fender washer, 1.25 inch OD, 5/16 inch inner	1	91525A230	McMaster-Carr
350 mL glass round bottom flask	1	CG-1880-42	Chemglass Scientific Equipment
1/8 inch NPT to ¼-28 Male	1	U-511	IDEX Health & Science
HPFA 360 µm OD, 100 µm ID tubing	1	1932	IDEX Health & Science
1/16 inch OD PTFE tubing	5 ft	1503	IDEX Health & Science
360 µm OD, 150 µm ID PTFE tubing	5 ft	1933	IDEX Health & Science
PEEK "T" Connector	1	P-714	IDEX Health & Science
Luer to ¼-28 adaptor	1	P-605	IDEX Health & Science
Capillary sleeves for 360 µm ID	1	F-185x	IDEX Health & Science
Billet refillable spray paint can	1	11181	Eastwood

APPENDIX B: Source code for the Arduino Uno microcontroller

The source code is provided without warranty. This version of the code, v1.0.1, does not implement a protocol for communicating with a computer. There are three sections to the code: the core, the ASL1600 Library, and the PID Library. The core code runs the Arduino Uno and calls upon the ASL1600 Library to communicate with the Sensirion ASL1600 flow meter and the PID Library to determine the pressure for a desired flow rate.

SEE ATTACHED CD FOR PROGRAM AND SOURCE CODE